

Tropospheric Emissions:  
Monitoring of Pollution



# Tropospheric Emissions: Monitoring of Pollution Overview

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GEO-CAPE 2015 Open  
Community Workshop  
August 31, 2015



Smithsonian





# Hourly atmospheric pollution from geostationary Earth orbit

**PI:** Kelly Chance, Smithsonian Astrophysical Observatory

**Instrument Development:** Ball Aerospace

**Project Management:** NASA LaRC

**Other Institutions:** NASA GSFC, NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska, RT Solutions, Carr Astronautics

**International collaboration:** Korea, U.K., ESA, Canada, Mexico

**Selected Nov. 2012 as NASA's first Earth Venture Instrument**

- Instrument being implemented, delivery May 2017
- NASA will arrange hosting on commercial geostationary communications satellite with launch expected NET 11/2018

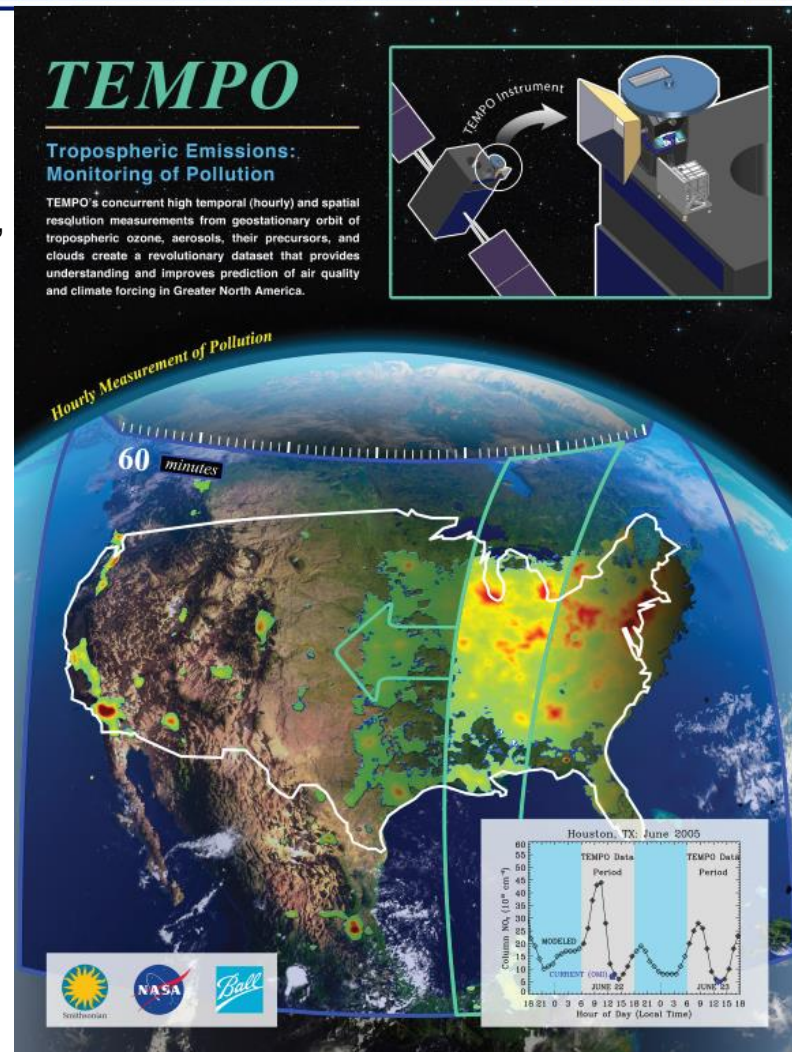
**Provides hourly daylight observations to capture rapidly varying emissions & chemistry important for air quality**

- UV/visible grating spectrometer to measure key elements in tropospheric ozone and aerosol pollution
- Exploits extensive measurement heritage from LEO missions
- Distinguishes boundary layer from free tropospheric & stratospheric ozone

**Aligned with Earth Science Decadal Survey recommendations**

- Makes many of the GEO-CAPE atmosphere measurements
- Responds to the phased implementation recommendation of GEO-CAPE mission design team

**North American component of an international constellation for air quality observations**



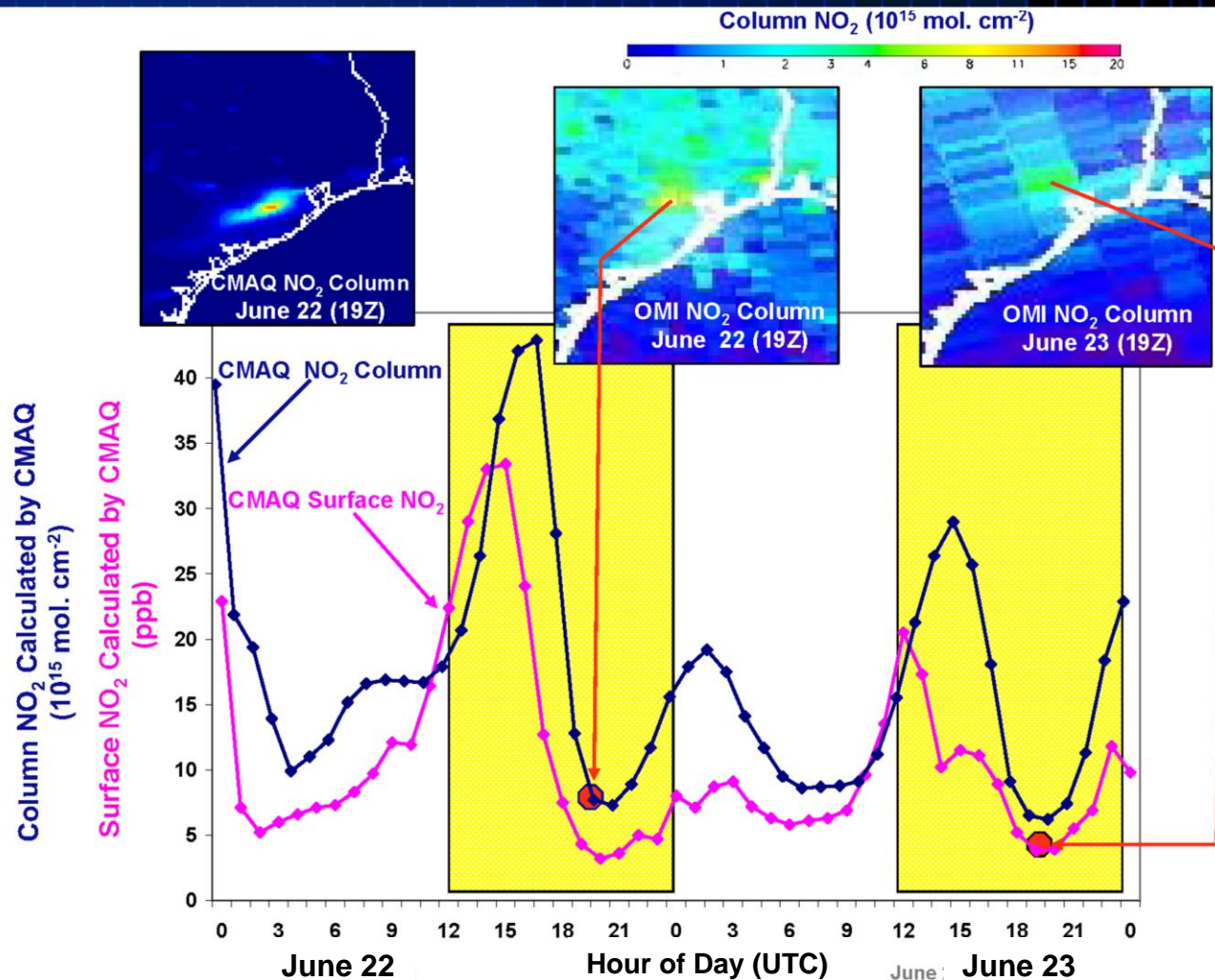


# The view from GEO



# Why geostationary? High temporal and spatial resolution

Hourly  $\text{NO}_2$  surface concentration and integrated column calculated by CMAQ air quality model: Houston, TX, June 22-23, 2005



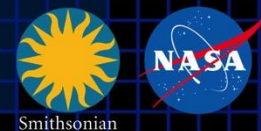
LEO observations provide limited information on rapidly varying emissions, chemistry, & transport

GEO will provide observations at temporal and spatial scales highly relevant to air quality processes

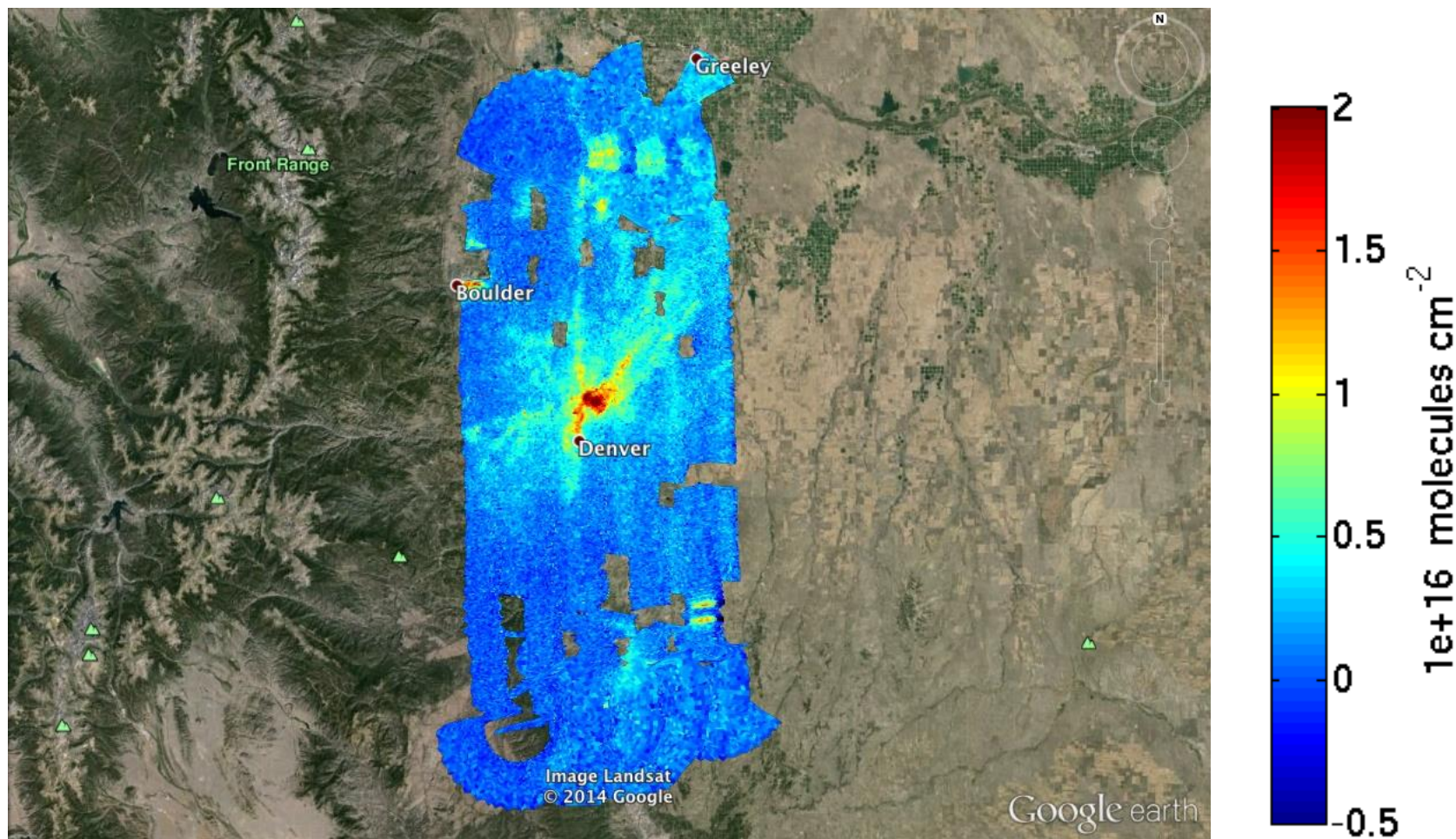




# TEMPO measurements will capture the diurnal cycle of pollutant emissions



## GeoTASO NO<sub>2</sub> Slant Column, 02 August 2014 **Morning**



Co-added to approx.  
500m x 450m

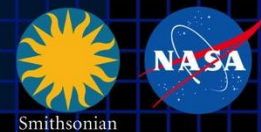
**Morning vs. Afternoon**

Preliminary data,  
C. Nowlan, SAO

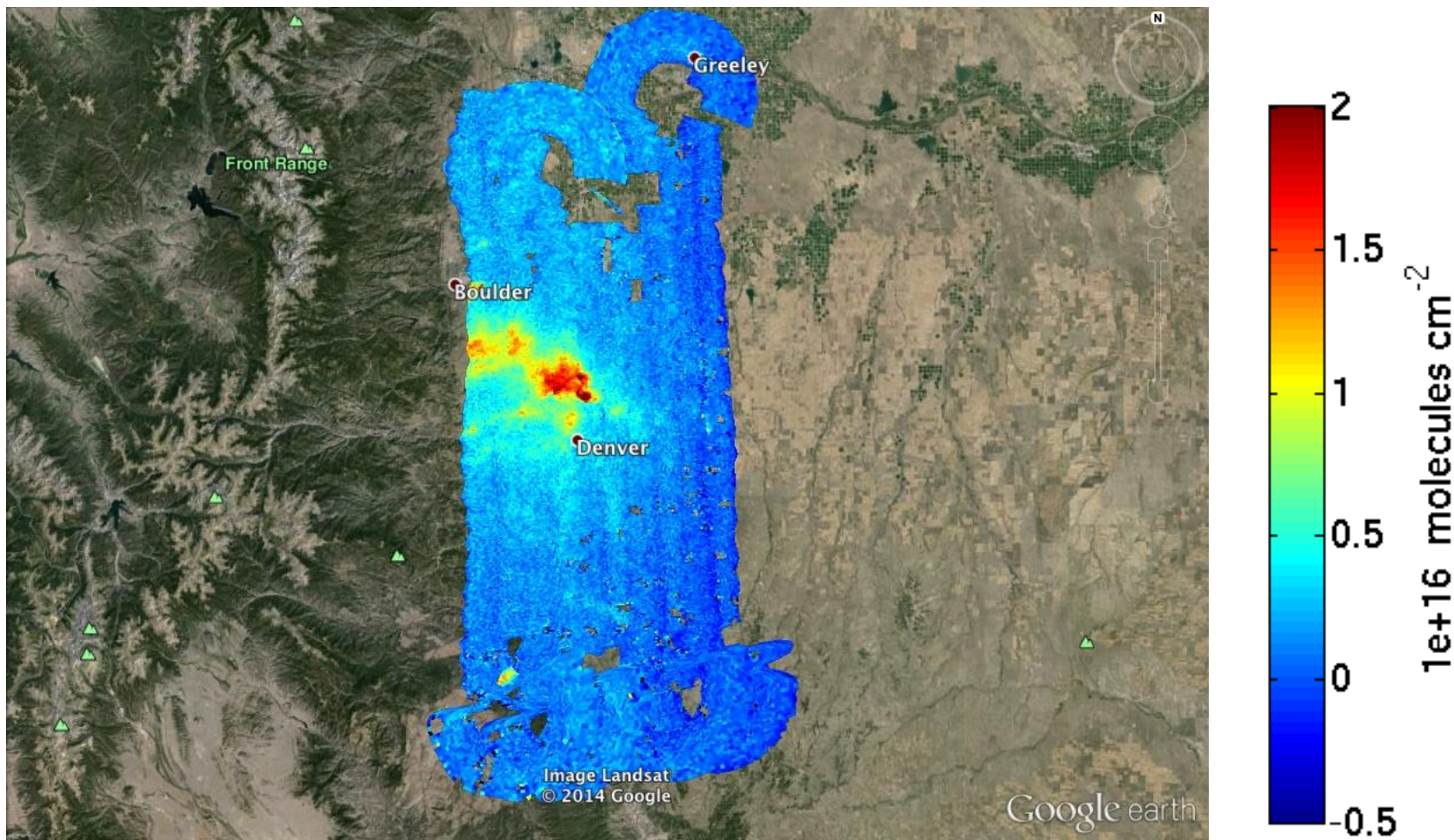




# TEMPO measurements will capture the diurnal cycle of pollutant emissions



## GeoTASO NO<sub>2</sub> Slant Column, 02 August 2014 **Afternoon**



Co-added to approx.  
500m x 450m

**Morning vs. **Afternoon****

**Preliminary data,  
C. Nowlan, SAO**

# TEMPO science traceability matrix

Science Questions	Science Objective	Science Measurement Requirement		Instrument Function Requirements			Investigation Requirements			
		Observables	Physical Parameters	Parameter	Required	Predicted				
<div>Q1: What are the temporal and spatial variations of emissions of gases and aerosols important for AQ and climate?</div> <div>Q2: How do physical, chemical, and dynamical processes determine tropospheric composition and AQ over scales ranging from urban to continental, diurnally to seasonally?</div> <div>Q3: How do episodic events affect atmospheric composition and AQ?</div> <div>Q4: How does AQ drive climate forcing and climate change affect AQ on a continental scale?</div> <div>Q5: How can observations from space improve AQ forecasts and assessments for societal benefit?</div> <div>Q6: How does trans-boundary transport affect AQ?</div>	<div>A: High temporal resolution measurements to capture changes in pollutant gas distributions. [Q1, Q2, Q3, Q4, Q5, Q6]</div> <div>B: High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas. [Q1, Q2, Q3, Q5, Q6]</div> <div>C: Measurement of major elements in tropospheric O<sub>3</sub> chemistry cycle, including multispectral measurements to improve sensing of lower-tropospheric O<sub>3</sub>, with precision to clearly distinguish pollutants from background levels. [Q1, Q2, Q4, Q5, Q6]</div> <div>D: Observe aerosol optical properties with high temporal and spatial resolution for quantifying and tracking evolution of aerosol loading. [Q1, Q2, Q3, Q4, Q5, Q6]</div> <div>E: Determine the instantaneous radiative forcings associated with O<sub>3</sub> and aerosols on the continental scale. [Q3, Q4, Q6]</div> <div>F: Integrate observations from TEMPO and other platforms into models to improve representation of processes in the models and construct an enhanced observing system. [Q1, Q2, Q3, Q5, Q6]</div> <div>G: Quantify the flow of pollutants across boundaries (physical &amp; political); Join a global observing system. [Q2, Q3, Q4, Q5, Q6]</div>	<div>Spatially imaged &amp; spectrally resolved, solar backscattered earth radiance, spanning spectral windows suitable for retrievals of O<sub>3</sub>, NO<sub>2</sub>, H<sub>2</sub>CO, SO<sub>2</sub> and C<sub>2</sub>H<sub>2</sub>O<sub>2</sub>. [A, B, C, E, F, G]</div> <div>Measurements at spatial scales comparable to regional atmospheric chemistry models. [A, B, C, D, F, G]</div> <div>Multispectral data in suitable O<sub>3</sub> absorption bands to provide vertical distribution information. [A, B, C, E, F, G]</div> <div>Spectral radiance measurements with suitable quality (SNR) to provide multiple measurements over daylight hours (solar zenith angle &lt; 70°) at precisions to distinguish pollutants from background levels. [A to G]</div> <div>Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles &lt;70°. [B, D, E, F, G]</div>	Baseline* Trace gas column densities (10 <sup>15</sup> cm <sup>-2</sup> ) hourly @ 8.9 km x 5.2 km					<div>Mission lifetime: 1-yr (Threshold), 20-mon (Baseline), 10-yr (Goal)</div> <div>Orbit Longitude °W: 90-110 (Preferred), 75-137 (Acceptable)</div> <div>GEO Bus Pointing: Control &lt;0.1° Knowledge &lt;0.04°</div> <div>On-orbit Calibration, Validation, Verification</div> <div>FOR encompasses CONUS and adjacent areas</div> <div>Provide near-real-time products to user communities within 2.5-hr to enable assimilation into chemical models (NOAA &amp; EPA) and use by smart-phone applications</div> <div>Distribute and archive TEMPO science data products</div>		
			Species	Precision	Band	Signal to Noise				
			O <sub>3</sub> : 0-2 km	10 ppbv	O <sub>3</sub> : Vis (540-650 nm) O <sub>3</sub> : UV (290-345 nm)	≥1413			1765	
			O <sub>3</sub> : FT	10 ppbv		≥1032			1247	
			O <sub>3</sub> : SOC	5%						
			O <sub>3</sub> : Total	3%						
			NO <sub>2</sub>	1.00	423-451 nm		≥781		2604	
			H <sub>2</sub> CO	17.3	327-354 nm		≥742		2266	
			SO <sub>2</sub>	17.3	305-330 nm		≥1100		1328	
			C <sub>2</sub> H <sub>2</sub> O <sub>2</sub>	0.70	433-465 nm		≥1972		2670	
			Baseline* Aerosol/Cloud properties hourly @ 8.9 km x 5.2 km							
			Property	Precision	Band		Signal to Noise			
			AOD	0.10	354, 388 nm		≥1414		2158	
			AAOD	0.06						
			AI	0.2						
			CF	0.05	346-354 nm		≥1200		2222	
			COCP	100 mb						
			Spectral Imaging Requirements							
			Relevant absorption bands for trace gases & windows for aerosols	Spectral Range (nm)		290-490, 540-740			290-490, 540-740	
				Spectral Resolution (nm)		≤0.6			0.6	
				Spectral Sampling (nm)		< 0.22			0.2	
			Radiometric Requirements							
			Solar irradiance and Earth backscattered radiance spectrally resolved over spectral range	Wavelength-dependent Albedo Calibration Uncert. (%)		≤1			0.8	
				Wavelength-independent Albedo Calibration Uncert. (%)		≤2			2.0	
				Spectral Uncertainty (nm)		< 0.02			< 0.02	
				Polarization Factor (%)		<5 UV, <20 Vis			≤4 UV, <20 Vis	
			Spatial Imaging Requirements							
Observations at relevant urban to synoptic scales and multiple times during daytime	Revisit Time (hr)		≤1		1					
	FOR		CONUS		GNA					
	Geolocation Uncertainty (km)		<4.0		2.8					
	IFOV*: N/S × E/W (km)		≤2.2 × ≤5.2		2.2 × 5.2					
	E/W Oversampling (%)		7.5 ± 2.5		7.5					
	MTF of IFOV*: N/S × E/W		≥0.16 × ≥0.30		0.16 × 0.36					



# Baseline and threshold data products

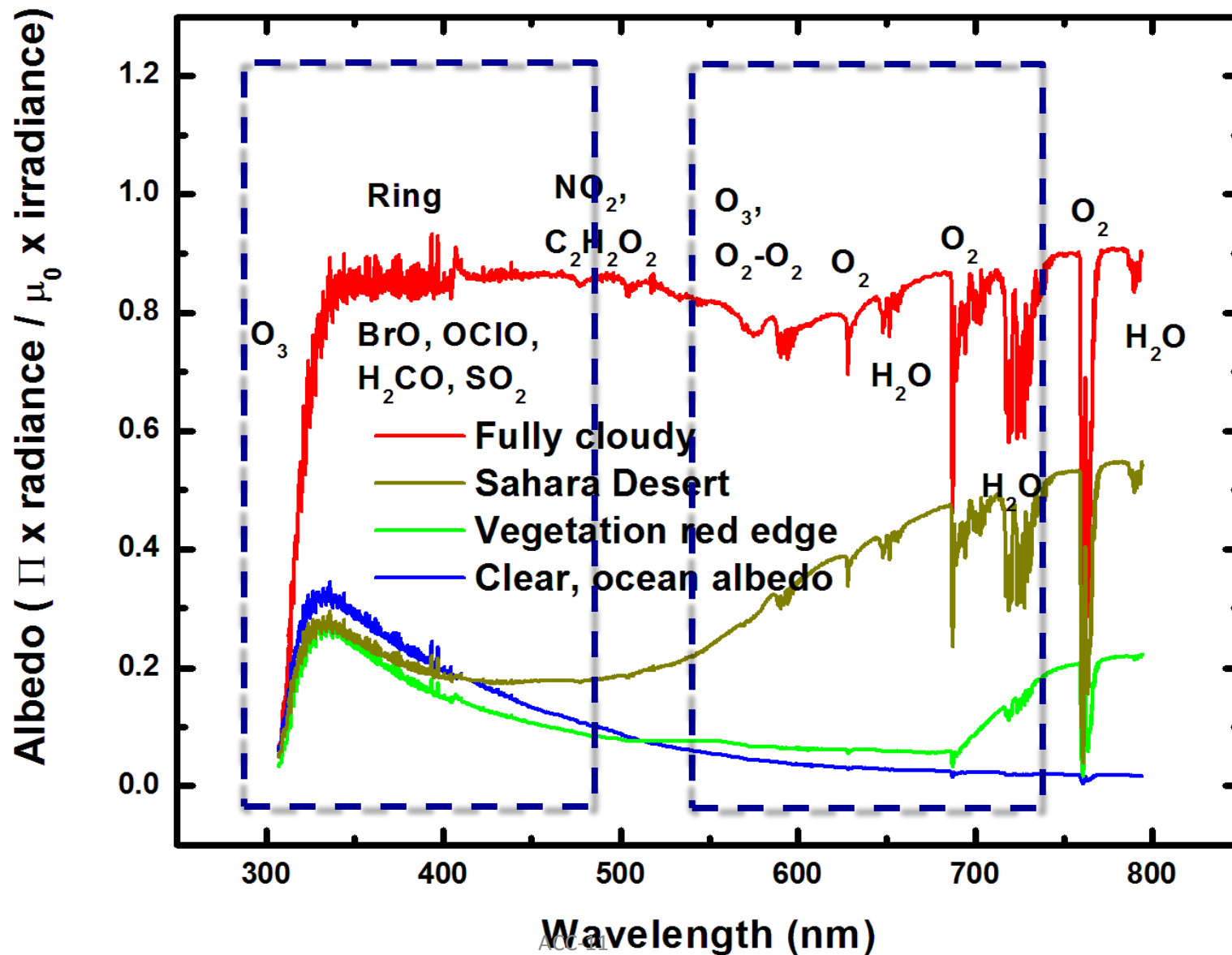
Species/Products	Required Precision	Temporal Revisit
0-2 km O <sub>3</sub> (Selected Scenes) <b>Baseline only</b>	10 ppbv	2 hour
Tropospheric O <sub>3</sub>	10 ppbv	1 hour
Total O <sub>3</sub>	3%	1 hour
Tropospheric NO <sub>2</sub>	$1.0 \times 10^{15}$ molecules cm <sup>-2</sup>	1 hour
Tropospheric H <sub>2</sub> CO	$1.0 \times 10^{16}$ molecules cm <sup>-2</sup>	3 hour
Tropospheric SO <sub>2</sub>	$1.0 \times 10^{16}$ molecules cm <sup>-2</sup>	3 hour
Tropospheric C <sub>2</sub> H <sub>2</sub> O <sub>2</sub>	$4.0 \times 10^{14}$ molecules cm <sup>-2</sup>	3 hour
Aerosol Optical Depth	0.10	1 hour

- Minimal set of products sufficient for constraining air quality
- Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N
- Data products at urban-regional spatial scales
  - Baseline  $\leq 60$  km<sup>2</sup> at center of Field Of Regard (FOR)
  - Threshold  $\leq 300$  km<sup>2</sup> at center of FOR
- Temporal scales to resolve diurnal changes in pollutant distributions
- Collected in cloud-free scenes
- Geolocation uncertainty of less than 4 km
- Mission duration, subject to instrument availability
  - Baseline 20 months
  - Threshold 12 months



- **Measurement technique**
  - Imaging grating spectrometer measuring solar backscattered Earth radiance
  - Spectral band & resolution: 290-490 + 540-740 nm @ 0.6 nm FWHM, 0.2 nm sampling
  - 2 2-D, 2kx1k, detectors image the full spectral range for each geospatial scene
- **Field of Regard (FOR) and duty cycle**
  - Mexico City/Yucatan Peninsula to the Canadian tar/oil sands, Atlantic to Pacific
  - Instrument slit aligned N/S and swept across the FOR in the E/W direction, producing a radiance map of Greater North America in one hour
- **Spatial resolution**
  - 2.1 km N/S × 4.7 km E/W native pixel resolution (9.8 km<sup>2</sup>)
  - Co-add/cloud clear as needed for specific data products
- **Standard data products and sampling rates**
  - Most sampled hourly, including eXcel O<sub>3</sub> (troposphere, PBL) for selected areas
  - H<sub>2</sub>CO, C<sub>2</sub>H<sub>2</sub>O<sub>2</sub>, SO<sub>2</sub> sampled hourly (average results for ≥ 3/day if needed)
  - Nominal spatial resolution 8.4 km N/S × 4.7 km E/W at center of domain (can often measure 2.1 km N/S × 4.7 km E/W)
  - Measurement requirements met up to 50° for SO<sub>2</sub>, 70° SZA for other products

# Typical TEMPO-range spectra (from ESA GOME-1)



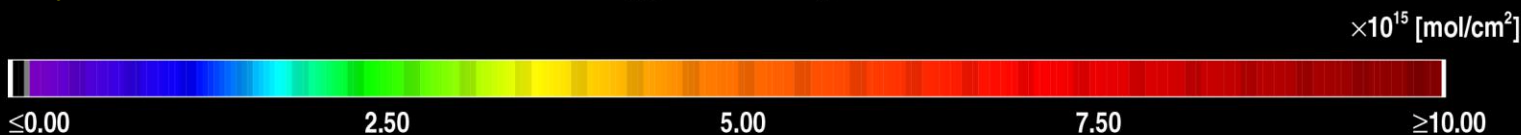


OMPS slant column  
H<sub>2</sub>CO monthly average  
for July 2012. Because of  
higher SNR, the OMPS  
precisions are  
substantially higher than  
those from OMI.



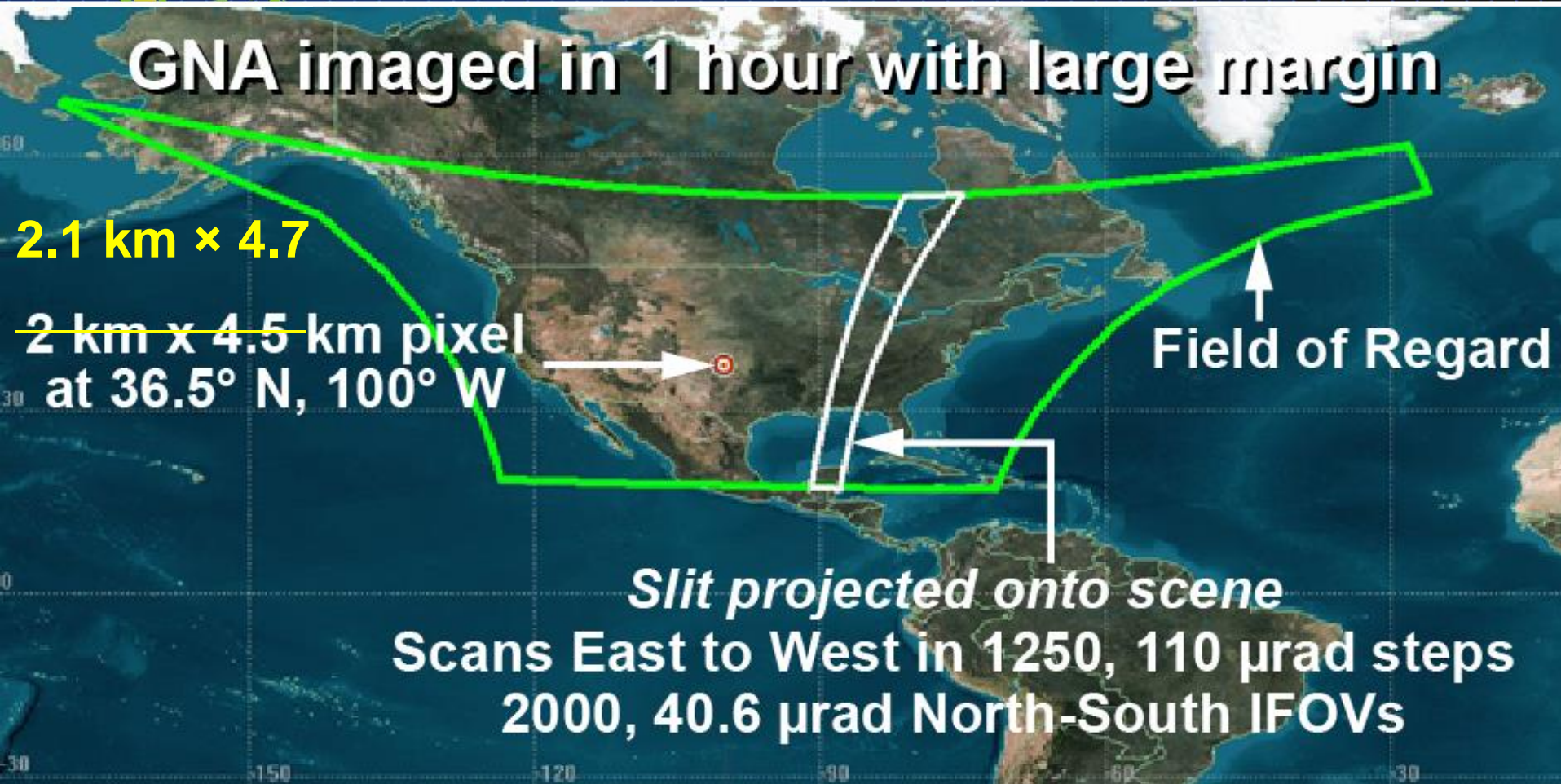


OMPS tropospheric slant column NO<sub>2</sub> for July 2-7, 2012. Much optimization remains to improve fitting and remove artifacts but the data are nearly of sufficient quality for scientific studies. The SAA is readily visible.



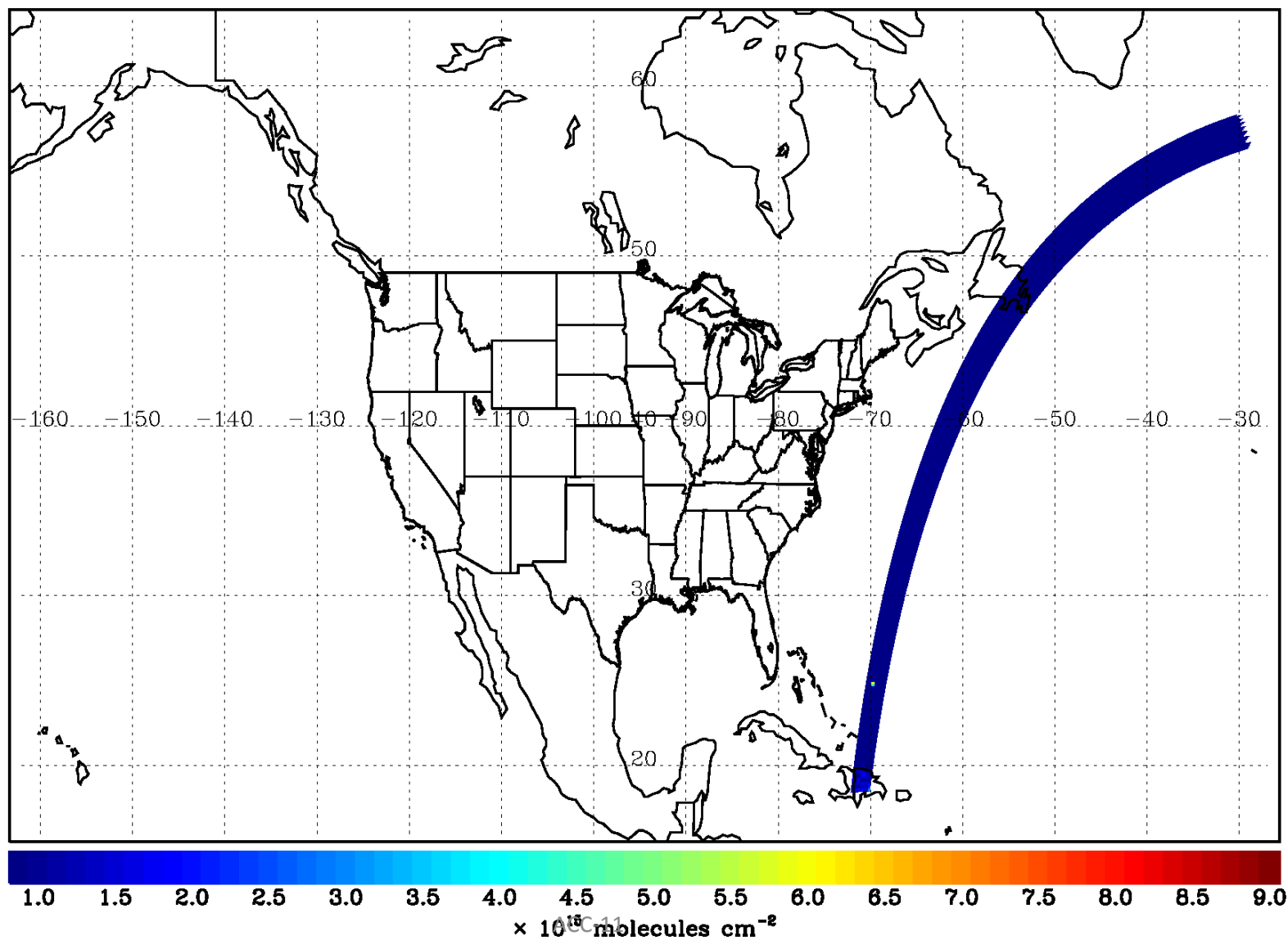


- **Geostationary orbit, operating on a commercial telecom satellite**
  - NASA will arrange launch and hosting services (per Earth Venture Instrument scope)
    - 80-115° W acceptable latitude
    - Specifying satellite environment, accommodation
  - Hourly measurement and telemetry duty cycle for at least  $\leq 70^\circ$  SZA
    - **Hope to measure up to 20 hours/day**
- **TEMPO is low risk with significant space heritage**
  - All proposed TEMPO measurements have been made from low Earth orbit satellite instruments to the required precisions
  - All TEMPO launch algorithms are implementations of currently operational algorithms
    - NASA TOMS-type  $O_3$
    - $SO_2$ ,  $NO_2$ ,  $H_2CO$ ,  $C_2H_2O_2$  from fitting with AMF-weighted cross sections
    - Absorbing Aerosol Index, UV aerosol, Rotational Raman scattering cloud
    - eXceL profile/tropospheric/PBL  $O_3$  for selected geographic targets
- **Example higher-level products: Near-real-time pollution/AQ indices, UV index**
- **TEMPO research products will greatly extend science and applications**
  - **Example research products:** eXceL profile  $O_3$  for broad regions; BrO from AMF-normalized cross sections; height-resolved  $SO_2$ ; additional cloud/aerosol products; vegetation products;  $H_2O$



***Each 2.1 km × 4.7 km pixel is a 2K element spectrum from 290-740 nm  
GEO platform selected by NASA for viewing Greater North America***



TEMPO hourly NO<sub>2</sub> sweepOMI NO<sub>2</sub> in April (2005–2008) over TEMPO FOR

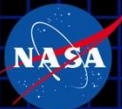
# Bay Area coverage





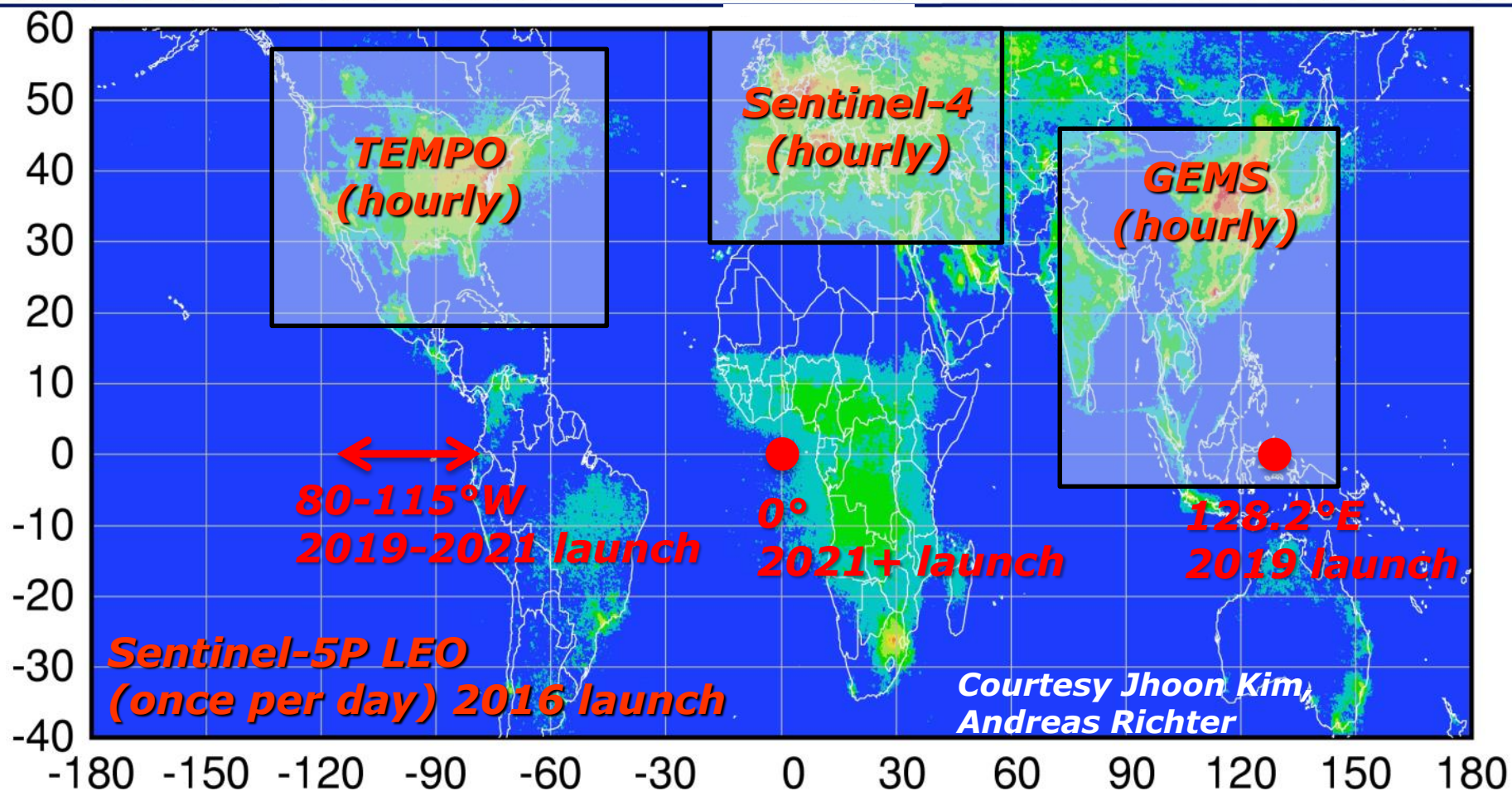


# Mexico City coverage





# Global pollution monitoring constellation



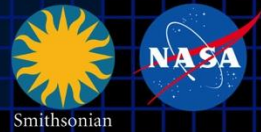
## Policy-relevant science and environmental services enabled by common observations

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support United Nations Convention on Long Range Transboundary Air Pollution

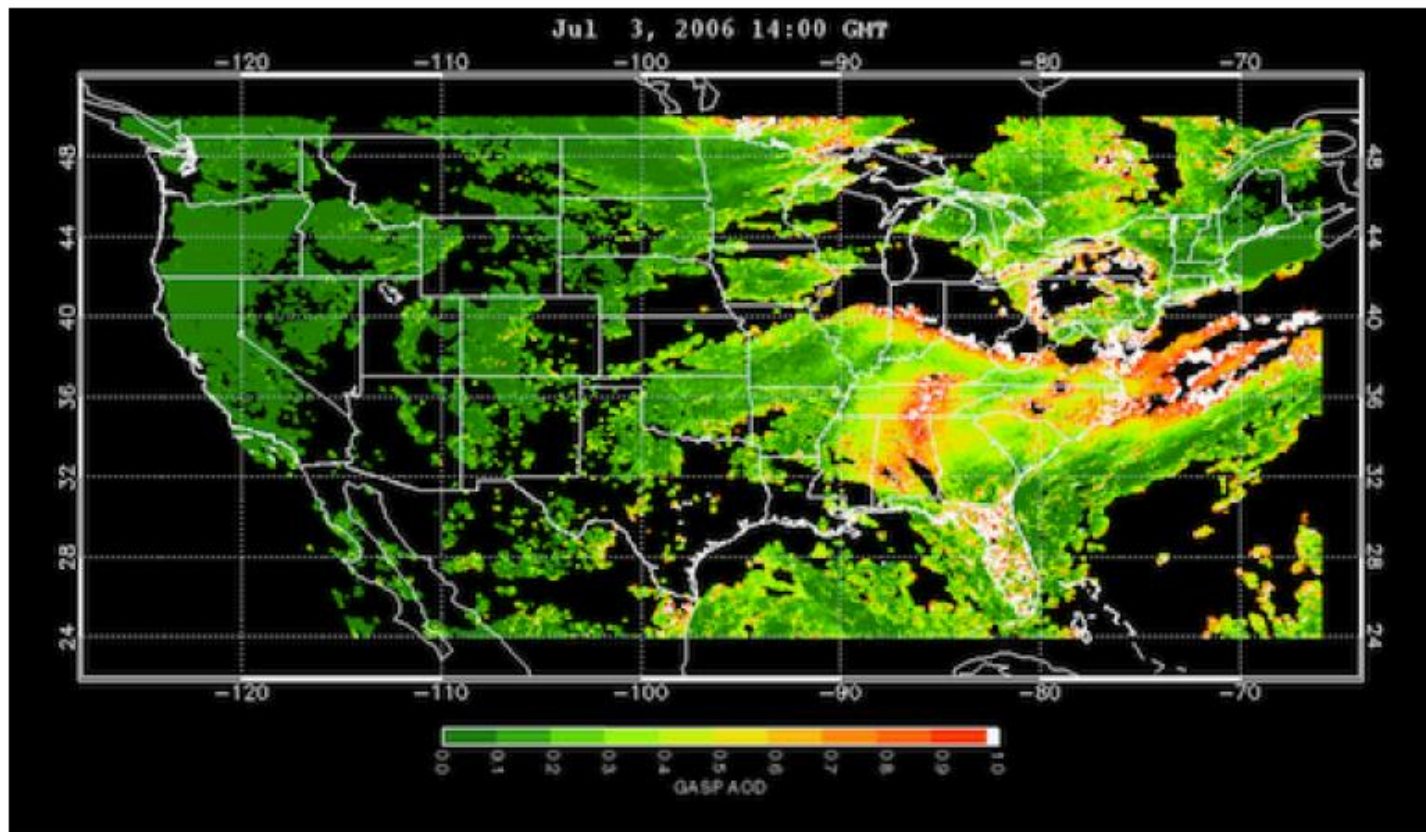




[www.epa.gov/rsig](http://www.epa.gov/rsig)



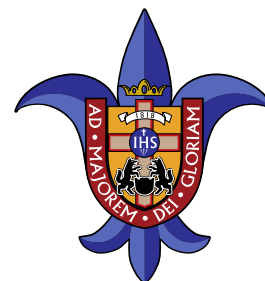
**TEMPO will use the EPA's Remote Sensing Information Gateway (RSIG) for subsetting, visualization, and product distribution – *to make TEMPO YOUR instrument***



- **Currently on-schedule and on-budget**
  - Passed PDR July, 2014
  - Converted instrument to firm fixed price March 2015
  - Now in Phase C: Passed KDP-C April, 2015
  - Addressing detector issues to ensure PBL O<sub>3</sub>
  - Ground systems development at SAO on schedule
- Passed instrument CDR June 2015
  - Reassessing operational data product list
  - Separate Ground Systems CDR March 2016
- Select satellite host probably in 2017
  - TEMPO operating longitude and launch date are not known until after host selection
- Instrument delivery 05/2017 for launch 11/2018 or later
  - Could be as late as 2021 but we hope not



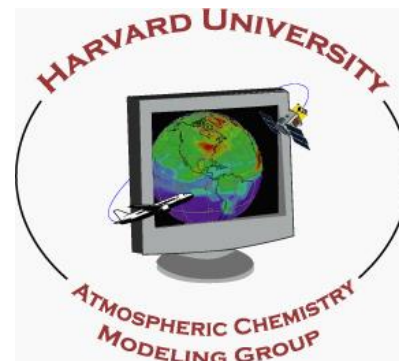
# The end!



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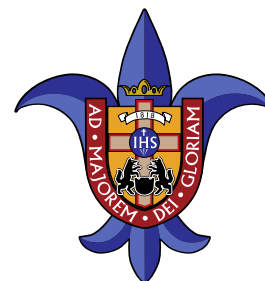
NCAR



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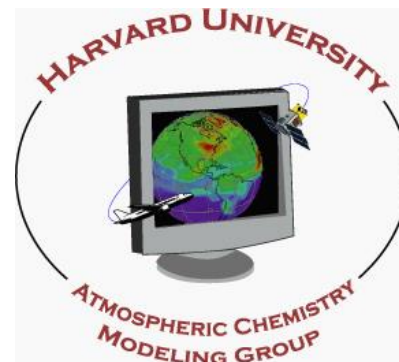
# Backups



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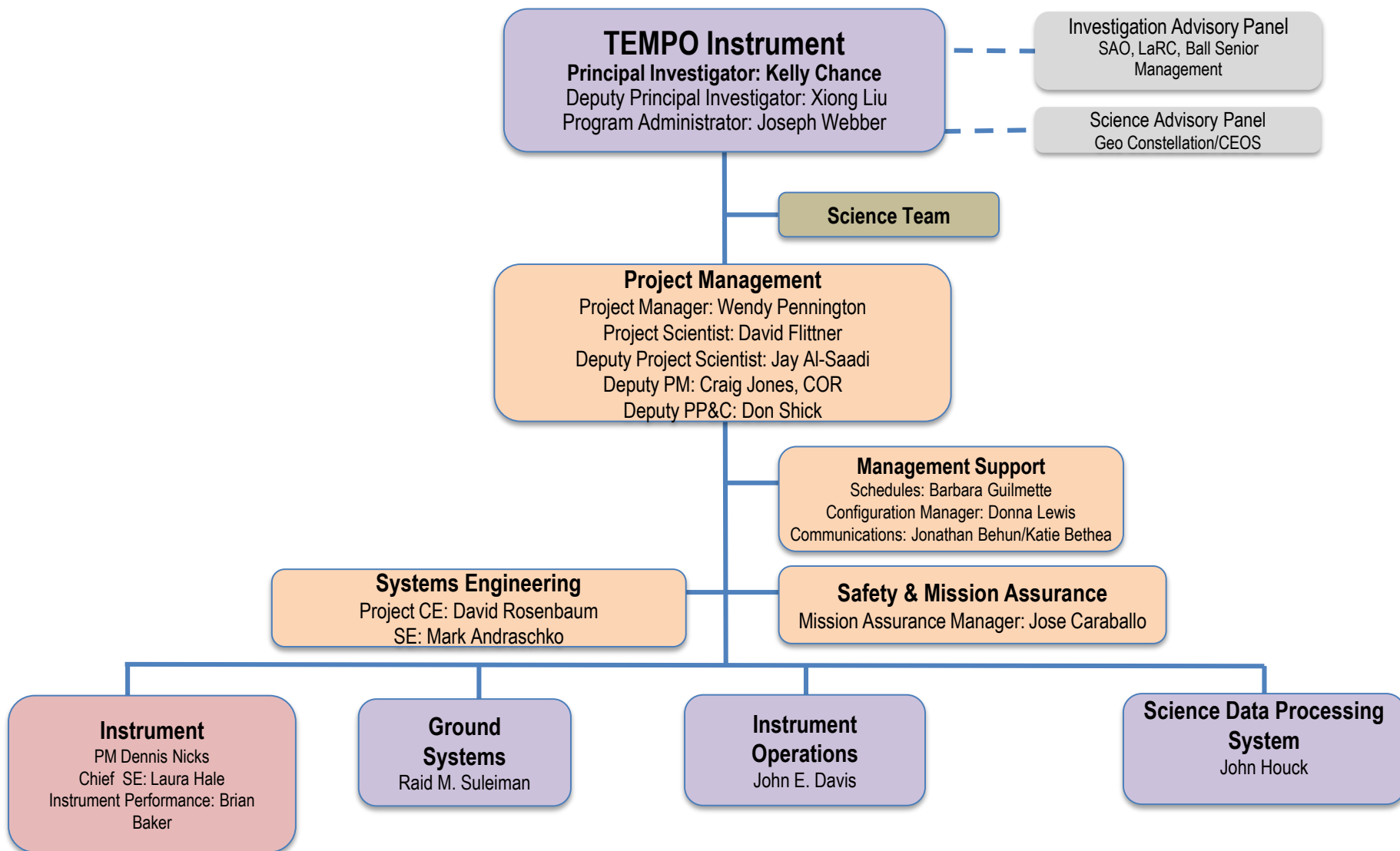
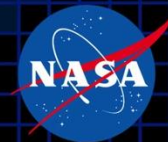


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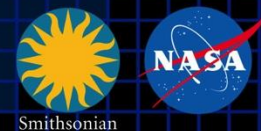


# TEMPO instrument project detailed organization structure





# TEMPO Science Team, U.S.



Team Member	Institution	Role	Responsibility
K. Chance	SAO	PI	Overall science development; <b>Level 1b, H<sub>2</sub>CO, C<sub>2</sub>H<sub>2</sub>O<sub>2</sub></b>
X. Liu	SAO	Deputy PI	Science development, data processing; <b>O<sub>3</sub> profile, tropospheric O<sub>3</sub></b>
J. Al-Saadi	LaRC	Deputy PS	Project science development
J. Carr	Carr Astronautics	Co-I	<b>INR Modeling and algorithm</b>
M. Chin	GSFC	Co-I	Aerosol science
R. Cohen	U.C. Berkeley	Co-I	NO <sub>2</sub> validation, atmospheric chemistry modeling, process studies
D. Edwards	NCAR	Co-I	VOC science, synergy with carbon monoxide measurements
J. Fishman	St. Louis U.	Co-I	AQ impact on agriculture and the biosphere
D. Flittner	LaRC	Project Scientist	Overall project development; STM; instrument cal./char.
J. Herman	UMBC	Co-I	Validation (PANDORA measurements)
D. Jacob	Harvard	Co-I	Science requirements, atmospheric modeling, process studies
S. Janz	GSFC	Co-I	Instrument calibration and characterization
J. Joiner	GSFC	Co-I	<b>Cloud, total O<sub>3</sub>, TOA shortwave flux research product</b>
N. Krotkov	GSFC	Co-I	<b>NO<sub>2</sub>, SO<sub>2</sub>, UVB</b>
M. Newchurch	U. Alabama Huntsville	Co-I	Validation (O <sub>3</sub> sondes, O <sub>3</sub> lidar)
R.B. Pierce	NOAA/NESDIS	Co-I	AQ modeling, data assimilation
R. Spurr	RT Solutions, Inc.	Co-I	<b>Radiative transfer modeling for algorithm development</b>
R. Suleiman	SAO	Co-I, Data Mgr.	Managing science data processing, <b>BrO, H<sub>2</sub>O, and L3 products</b>
J. Szykman	EPA	Co-I	AIRNow AQI development, validation (PANDORA measurements)
O. Torres	GSFC	Co-I	<b>UV aerosol product, AI</b>
J. Wang	U. Nebraska	Co-I	Synergy w/GOES-R ABI, <b>aerosol research products</b>
J. Leitch	Ball Aerospace	Collaborator	Aircraft validation, instrument calibration and characterization
D. Neil	LaRC	Collaborator	GEO-CAPE mission design team member

4/29/15

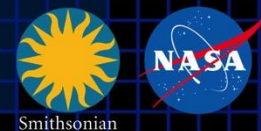
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# TEMPO Science Team, non-U.S.



Team Member	Institution	Role	Responsibility
R. Martin	Dalhousie U.	Collaborator	Atmospheric modeling, air mass factors, AQI development
Chris McLinden	Environment Canada	Collaborator	Canadian air quality coordination
Michel Grutter de la Mora	UNAM, Mexico	Collaborator	Mexican air quality coordination
Gabriel Vazquez	UNAM, Mexico	Collaborator	Mexican air quality, algorithm physics
Amparo Martinez	INECC, Mexico	Collaborator	Mexican environmental pollution and health
J. Victor Hugo Paramo Figueiroa	INECC, Mexico	Collaborator	Mexican environmental pollution and health
Brian Kerridge	Rutherford Appleton Laboratory, UK	Collaborator	Ozone profiling studies, algorithm development
Paul Palmer	Edinburgh U., UK	Collaborator	Atmospheric modeling, process studies
J. Kim	Yonsei U.	Collaborators, Science Advisory Panel	Korean GEMS, CEOS constellation of GEO pollution monitoring
C.T. McElroy	York U. Canada		CSA PHEOS, CEOS constellation of GEO pollution monitoring
B. Veihelmann	ESA		ESA Sentinel-4, CEOS constellation of GEO pollution monitoring

# TEMPO mission project integrated master schedule



## TEMPO Mission Project

March 2015 Host Award, Nov. 2018 Launch (NET)

Project Manager: Alan Little, LaRC

Status Date: Oct. 24, 2013



FY13		FY14				FY15				FY16				FY17				FY18				FY19				FY20
Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1

### 01 PROJECT MANAGEMENT

Host Contract Development

### 02 SYSTEMS ENGINEERING

Instrument Project milestones for reference only. Refer to TEMPO Instrument Project for full details.

### 05 INSTRUMENT

### 06 SPACECRAFT

Host Accommodations Development

Mission driven by approximate, notional timeline of owner-operator commercial satellite acquisition cycle correlated to TEMPO Instrument Delivery. Schedule represents earliest possible dates.

Notional Timeline of Commercial Satellite Acquisition

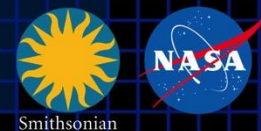
TEMPO-01-1003







# Data product definitions and details

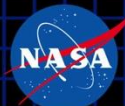


Data Product	Description	Time beyond on-orbit checkout to deliver initial data	Maximum data latency after first release for $\geq 80\%$ of all products <sup>†</sup>
Level 0	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
Level 1b	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
Level 2	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO
Level 3	Derived Gridded Geophysical Data Products	6 months	1 month after completion of data accumulation required for individual geophysical products

**All original observation data and standard science data products listed here, along with the scientific source code for algorithm software, coefficients, and ancillary data used to generate these products, shall be delivered to the designated NASA SMD/ESD-assigned DAAC within six months of completion of the prime mission. *Data products are publicly distributed during the mission.***

**<sup>†</sup>80% of the products, not 80% of the product types, will be produced within this latency time.**

# Instrument progress since KDP-B



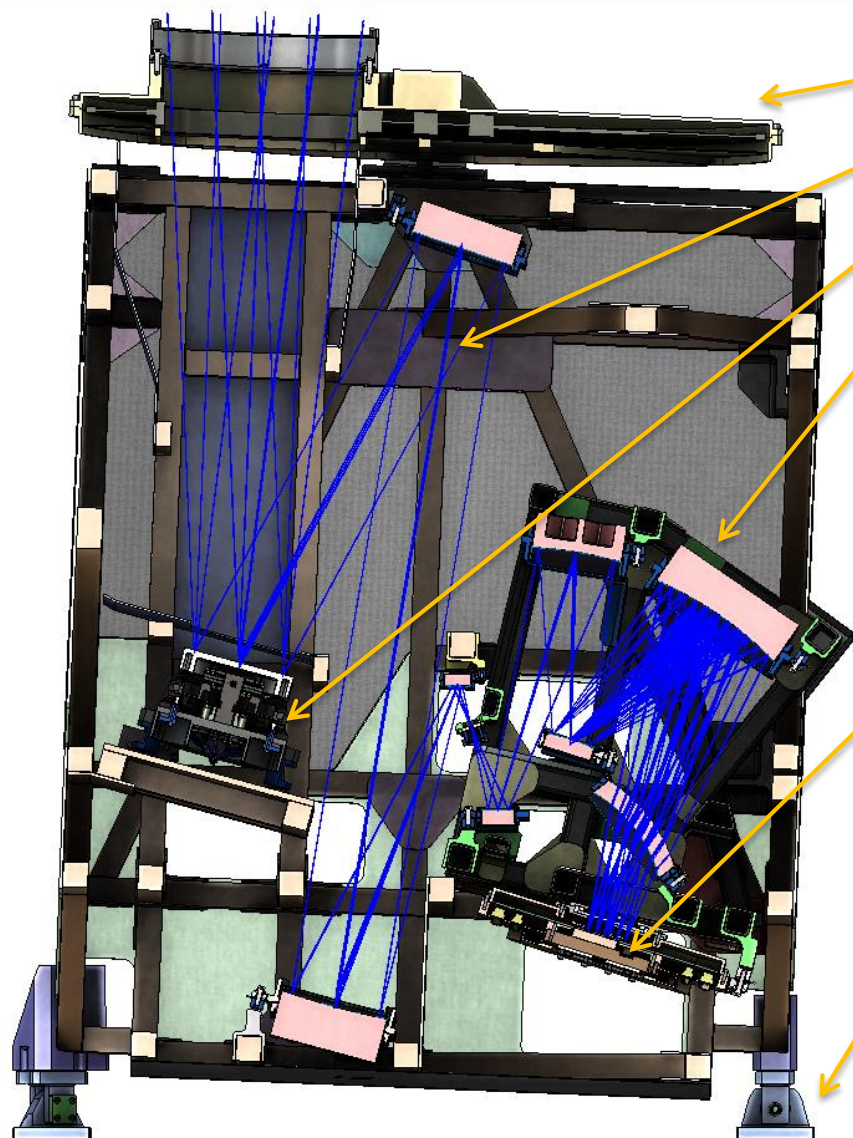
## **TIM @ Ball in April plus follow-on studies:**

- **S/N now meets reqs. with high margin (engineering & retrieval studies)**
- **Wavelength stability accepted, will use cross-correlation algorithm solution**
- **Polarization sensitivity modeled to be acceptable with high margin**
- **Field of regard (instrument plus mission jitter budget) resolved by changing acceptable range, still including Mexico City, Canadian oil sands**
- **N/S modulation transfer function (MTF) issue resolved by analysis**
  - May reduce MTF requirements to threshold near slit edge, beyond CONUS
- **Stray light modeled to be well within acceptable levels**
  - Stray light instrument specifications now accepted
  - Stray light knowledge and levels are nominal for this type of instrument (GOME, SCIA, OMI, OMPS)
  - Normal stray light correction is in 0-1 algorithm, as planned. Low risk of additional resources being required
  - Developing details of verification/characterization/calibration/testing is normal planned engineering work

**The TEMPO instrument design is capable of meeting Baseline Level 1 science requirements**



# Instrument layout



Calibration Mechanism Assembly

Telescope Assembly

Scan Mechanism Assembly

Spectrometer Assembly

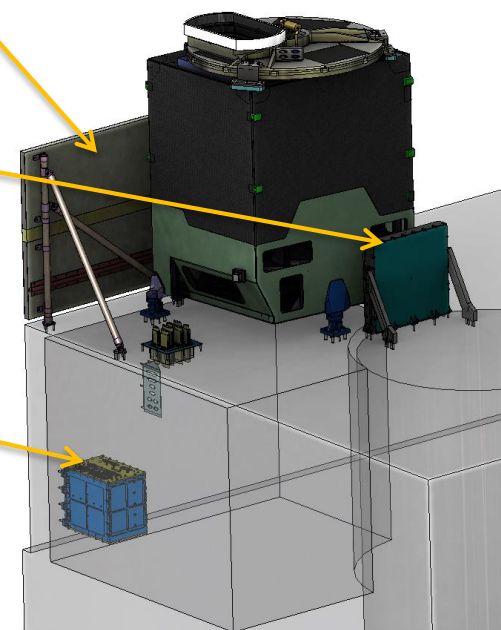
Radiator Assembly

Focal Plane  
Electronics

Focal Plane  
Assembly

Instrument  
Control Electronics

Instrument Support  
Assembly





# UV/Visible/IR satellite array spectrometers

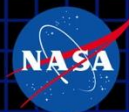


Instrument	Wavelength (nm)	Viewing Geometry	Gases	Launch Year
GOME (GOME-2)	240-790	Nadir	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, H <sub>2</sub> O	1995 (2006, 2012)
OSIRIS/ODIN	280-800	Limb	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, H <sub>2</sub> O	2001
SAGE III	280-1040	occultation (limb)	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, H <sub>2</sub> O	2001
GOMOS/Envisat	250-952	stellar occultation	O <sub>3</sub> , NO <sub>2</sub> , H <sub>2</sub> O, NO <sub>3</sub>	2002
SCIAMACHY/Envisat	240-2380	nadir/limb/occultation	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, CHO-CHO, H <sub>2</sub> O, NO <sub>3</sub> , N <sub>2</sub> O, CH <sub>4</sub> , CO, CO <sub>2</sub>	2002
MAESTRO/ACE	285-1030	occultation	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, H <sub>2</sub> O	2003
OMI/AURA	270-500	nadir	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, CHO-CHO	2004
OPUS/GCOM	306-420	nadir	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO	2006
OMPS/NPOESS	250-1000	nadir/limb	O <sub>3</sub> , NO <sub>2</sub> , BrO, OClO, SO <sub>2</sub> , HCHO, H <sub>2</sub> O	2011

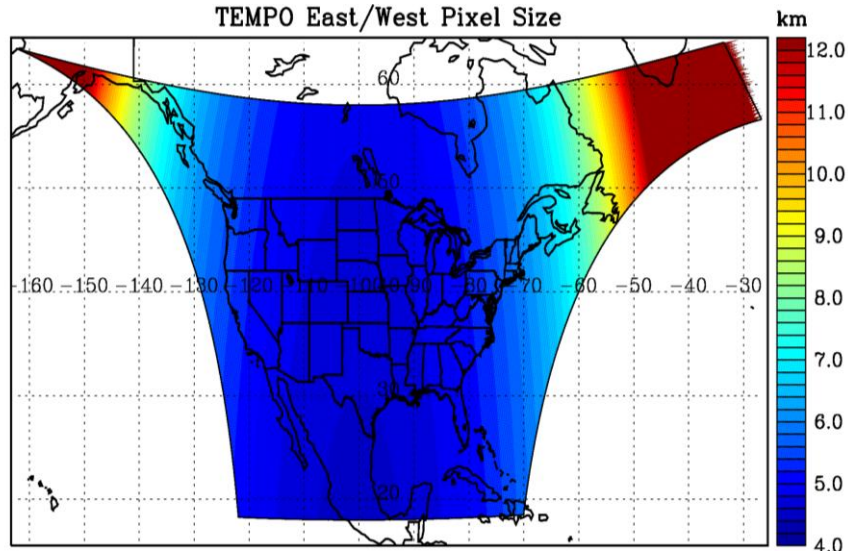




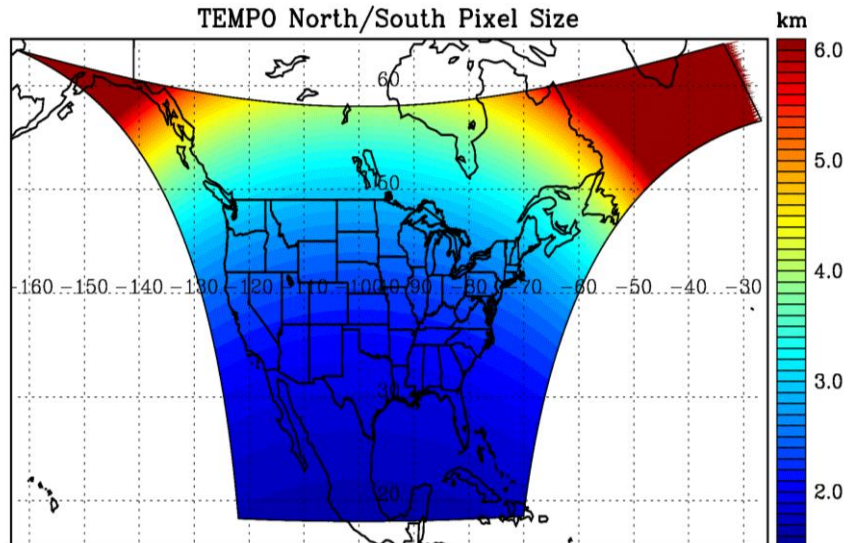
# Footprint comparison



TEMPO East/West Pixel Size



TEMPO North/South Pixel Size

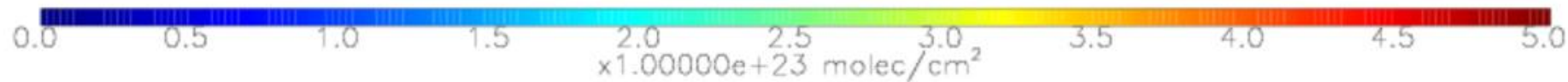
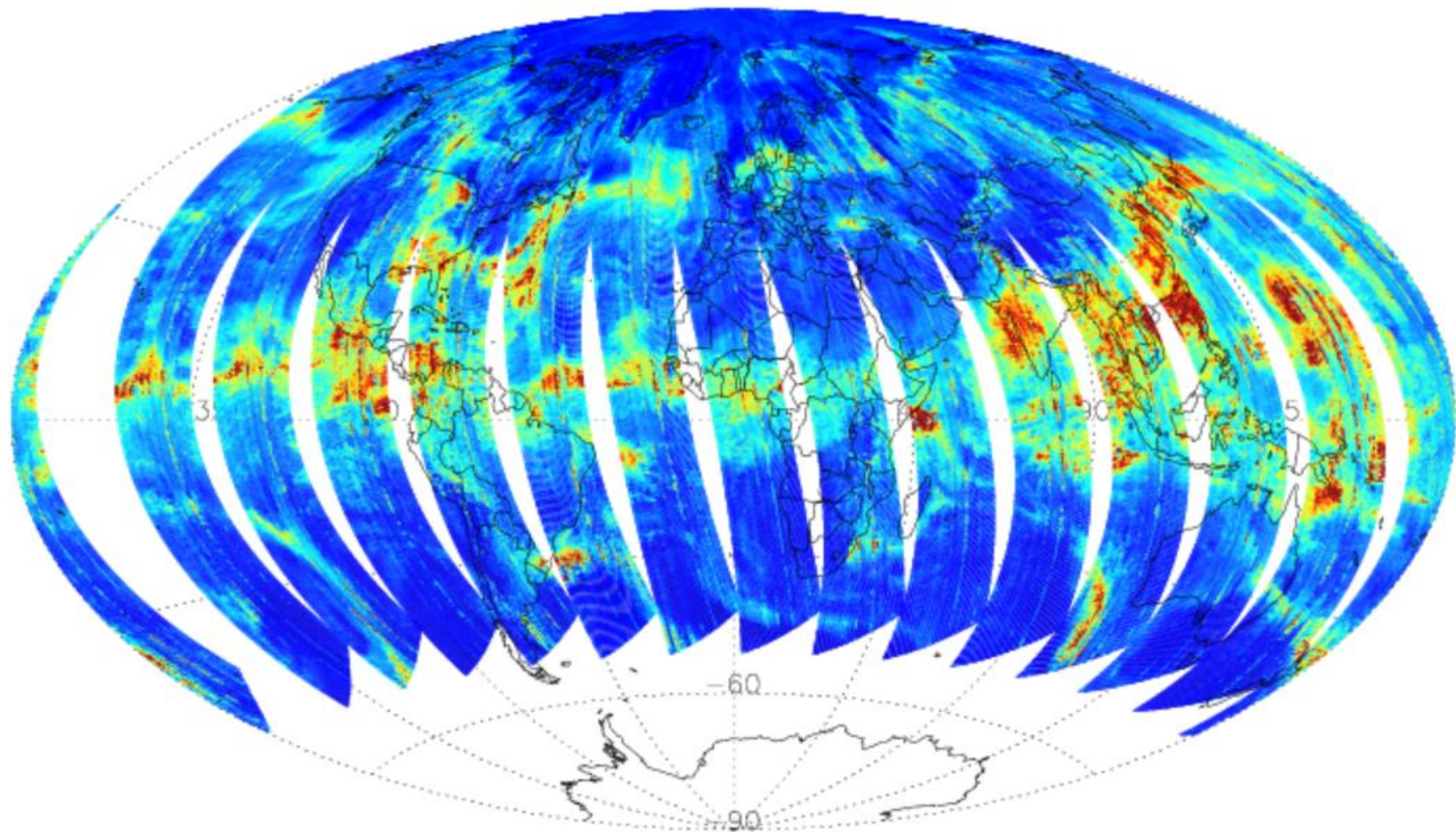


Location	N/S (km)	E/W (km)	GSA (km <sup>2</sup> )
36.5°N, 100°W	2.11	4.65	9.8
Washington, DC	2.37	5.36	11.9
Seattle	2.99	5.46	14.9
Los Angeles	2.09	5.04	10.2
Boston	2.71	5.90	14.1
Miami	1.83	5.04	9.0
Mexico City	1.65	4.54	7.5
Canadian tar sands	3.94	5.05	19.2

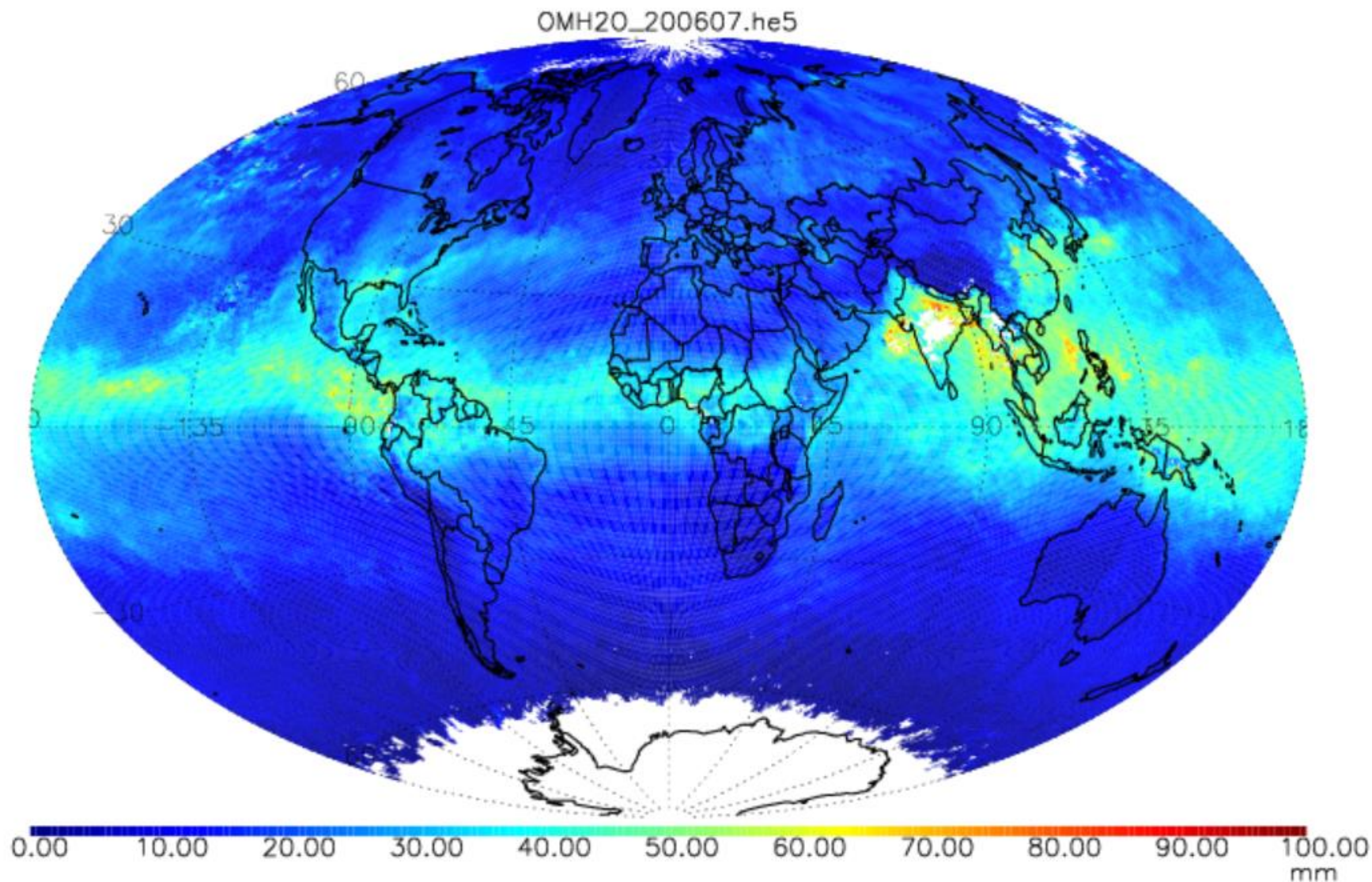
**Assumes 2000 N/S pixels**

**For GEO at 80°W, pixel size at  
36.5°N, 100°W is 2.2 km × 5.2 km.**







SAO L3 OMI H<sub>2</sub>O product



## Three changes were made to the TEMPO PLRA soon after KDP-B

1. Reduce the number of operational data products to focus on the most fundamental tropospheric air pollution chemistry;
2. Relax the field of regard slightly, but still covering CONUS, Mexico City and the Canadian oil sands;
3. Revise the acceptable longitude range for GEO hosts to 80°W to 115°W to be consistent with baseline science (a range demonstrated to include suitable candidates).

## With these changes:

- Key science measurements remain intact.
- Ball has a complete set of requirements that can be met at an acceptable level of risk.
- Savings in science budget of \$1.25M.

**As a result of SAO/LaRC/Ball technical interchange meetings and follow-on studies:**

- **Detectors can produce PLRA baseline products (engineering & retrieval studies)**
  - Assumptions included current predicted worst-case dark current
  - The largest impact of dark current is on the ozone retrieval products
  - The Science Team has quantified the degradation in ozone retrieval performance and believes PLRA baseline can be met with the current design, albeit with no margin remaining
- **Wavelength stability accepted, will use cross-correlation algorithm solution**
- **Polarization sensitivity modeled to be acceptable with high margin**
- **Field of regard (instrument plus mission jitter budget) resolved by changing acceptable range, still including Mexico City, Canadian oil sands**
- **N/S modulation transfer function (MTF) issue resolved by analysis**
- **Stray light modeled to be well within acceptable levels**

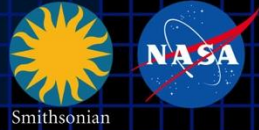


**Adjusting the field of regard (FOR) requirement from 18°N – 58°N to 19°N – 57.5°N (baseline) still allows, with the current BATC preliminary optical design, the measurement of both Mexico City and the Canadian oil sands, even if the maximum spacecraft pointing error permitted by the IHIRD is realized. The threshold is adjusted from 18°N – 55°N to 19°N – 55°N.**

- This change avoids cost risk on the Mission side by accepting the maximum allowed pointing error from the IHIRD rather than finding a way to mitigate it**
- This change may avoid risk on the Instrument side if the error budget independent of the IHIRD exceeds the specifications, thus requiring resources to improve instrument pointing**
- If the spacecraft pointing error is lower than the IHIRD maximum, the guaranteed field of regard will increase**



# Host longitude



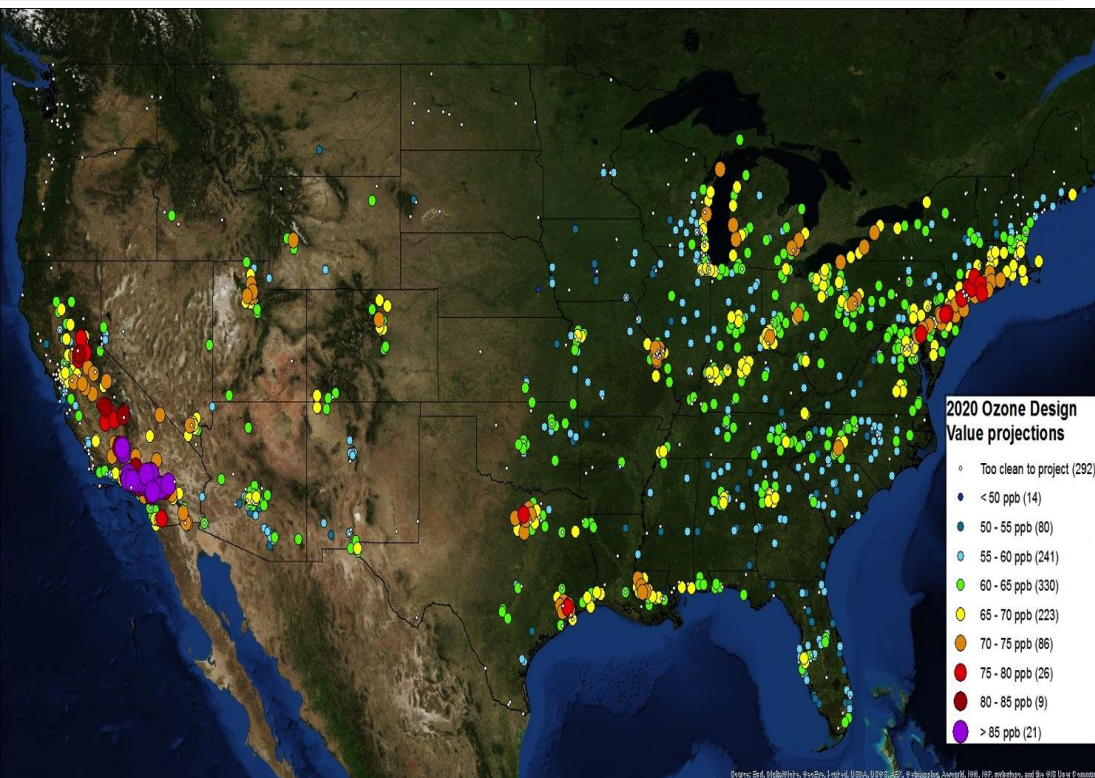
**Revising the acceptable longitude range for GEO hosts from 175°W – 137°W to 80°W – 115°W improves the ground footprint and improves diurnal coverage.**

- **The proposed range has been demonstrated to include many suitable candidates**
- **New orbital longitude range to 120° W is being analyzed for feasibility by the Instrument contractor to open the host opportunities**



- US air quality standards continue to become more stringent to better protect human health
- New and transient pollution sources (e.g., vehicular traffic, oil & gas development, trans-boundary pollution) are growing in importance yet are very difficult to monitor from ground networks
- Many areas that are not currently monitored are expected to violate proposed ozone standards
- TEMPO measurements will provide data to help solve this national challenge

## US EPA ozone 8-hour design projections to 2020



## TEMPO science questions

1. What are the temporal and spatial variations of **emissions** of gases and aerosols important for air quality and climate?
2. How do physical, chemical, and dynamical **processes** determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally?
3. How does air pollution drive **climate** forcing and how does climate change affect **air quality** on a continental scale?
4. How can observations from space improve air quality **forecasts and assessments**?
5. How does **intercontinental transport** affect air quality?
6. How do **episodic events**, such as wild fires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality?



# Title

